ECE 371
Materials and Devices

11/14/19 - Lecture 22

Ch. 8 – Forward Biased pn-Junctions, Excess Minority Carrier Concentrations, Ideal Diode Equation

General Information

- Homework 6 solutions posted
- Homework 7 assigned and due Thursday 11/21
- Midterm 2 solutions posted
- Reading for next time: 10.1

Biased pn Junctions

- No current due to potential barrier
- E is all built in to junction

- Potential barrier increases
- Still no current
- E increases
- Fermi levels separate

- Potential barrier decreases
- E decreases
- Electrons and holes diffuse across junction
- Current flows

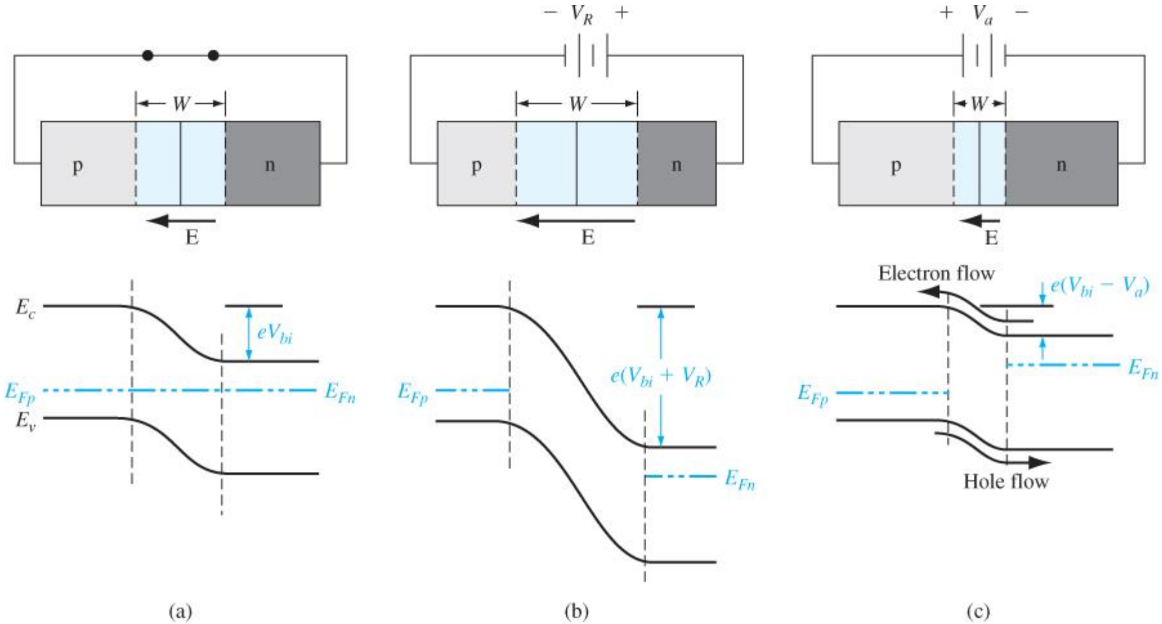


Figure 8.1 | A pn junction and its associated energy-band diagram for (a) zero bias, (b) reverse bias, and (c) forward bias.

pn Junction - Forward Bias

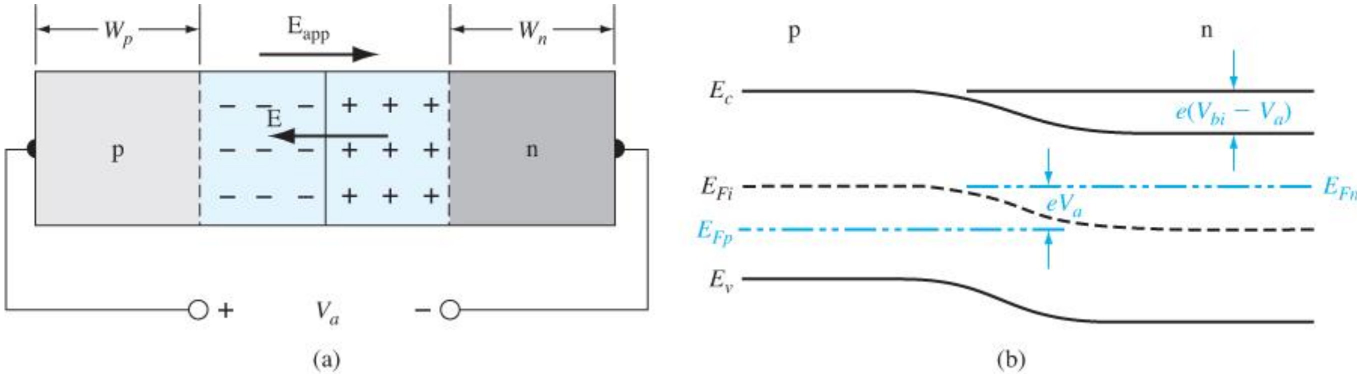


Figure 8.3 | (a) A pn junction with an applied forward-bias voltage showing the directions of the electric field induced by V_a and the space charge electric field. (b) Energy-band diagram of the forward-biased pn junction.

- Positive bias reduces potential barrier ($V_{bi} \rightarrow V_{bi} - V_a$)
- All applied bias is assumed to drop across depletion region
- E_{app} and E_{bi} are in opposite directions (total E is reduced)
- No longer have the drift/diffusion balance we had in thermal equilibrium
- Electrons and holes diffuse across the depletion region and produce a current as long as the applied bias continues

Minority Carrier Concentrations With Applied Bias

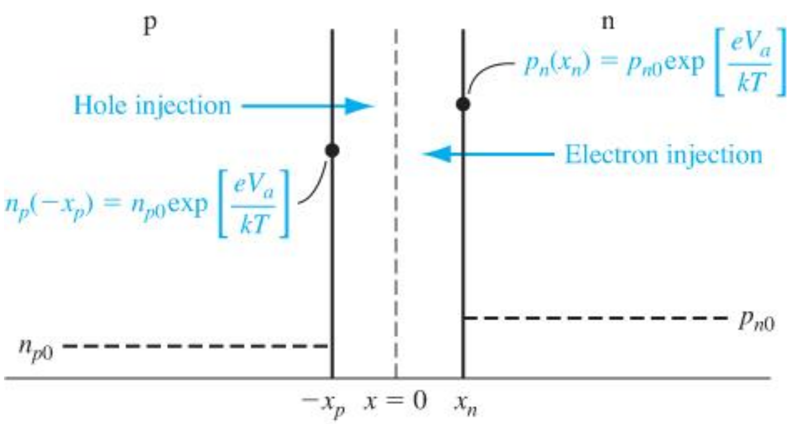


Figure 8.4 | Excess minority carrier concentrations at the space charge edges generated by the forward-bias voltage.

Total non-thermal equilibrium minority carrier concentrations at the depletion region edges

$$\boxed{n_p = n_p(-x_p) = n_{p_0} exp\left(\frac{eV_a}{kT}\right)}$$

$$\boxed{p_n = p_n(x_n) = p_{n_0} exp\left(\frac{eV_a}{kT}\right)}$$

- pn junction current is diffusion-based
- Holes inject into the n-side and electrons inject into the p-side
- Minority carrier concentrations can increase by many orders of magnitude under forward bias
- Majority carrier concentrations remain nearly constant under low-level injection
- Minority carrier concentrations are maximum at the depletion region edges and decay away from the edges due to diffusion and recombination

Transport Equations (from Ch. 6)

- The ambipolar transport equations describe the behavior of minority carriers as a function of space and time (Ch. 6)

$$\boxed{D_n \frac{\partial^2(\delta n_p)}{\partial x^2} + \mu_n E \frac{\partial(\delta n_p)}{\partial x} + g' - \frac{\delta n_p}{\tau_{n0}} = \frac{\partial(\delta n_p)}{\partial t}}$$

*electrons in p-region

$$\boxed{D_p \frac{\partial^2(\delta p_n)}{\partial x^2} - \mu_p E \frac{\partial(\delta p_n)}{\partial x} + g' - \frac{\delta p_n}{\tau_{p0}} = \frac{\partial(\delta p_n)}{\partial t}}$$

*holes in n-region

diffusion

drift

generation

recombination

change in time

- g’ = generation rate of excess carriers [#/(cm^3 s)]
- τ = minority carrier lifetime under low-level injection

Transport Equations (from Ch. 6)

- The transport equations can be simplified with the following assumptions
  1. The electric field is approximately zero in the quasi-neutral regions*
  2. The system is in steady state (e.g., $\frac{\partial(\delta n_p)}{\partial t} = 0$)
  3. There is no generation in the quasi-neutral regions or the depletion region. Generation only occurs right at the contacts.

$$\boxed{\frac{d^2(\delta n_p)}{dx^2} - \frac{\delta n_p}{L_n^2} = 0}$$

*electrons in p-region ($x \leq -x_p$)

$$\boxed{\frac{d^2(\delta p_n)}{dx^2} - \frac{\delta p_n}{L_p^2} = 0}$$

*holes in n-region ($x \geq x_n$)

- Retain diffusion and recombination terms only
- $L_n^2 = D_n \tau_{n0}$ and $L_p^2 = D_p \tau_{p0}$ are the minority carrier diffusion lengths

*Actually, it is not exactly zero, just small, and is needed to supply drift of majority carriers to replenish the majority carriers that diffuse to the opposite side of the junction or recombine with injected minority carriers

Minority Carrier Distributions

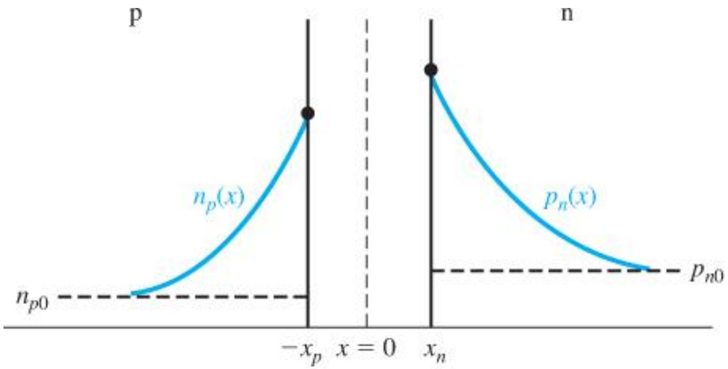


Figure 8.5 | Steady-state minority carrier concentrations in a pn junction under forward bias.

$$\boxed{\delta p_n(x) = p_{n0}\left[exp\left(\frac{eV_a}{kT}\right) - 1\right] exp\left[\frac{x_n - x}{L_p}\right]}$$

$$(x \geq x_n)$$

$$\boxed{\delta n_p(x) = n_{p0}\left[exp\left(\frac{eV_a}{kT}\right) - 1\right] exp\left[\frac{x_p + x}{L_p}\right]}$$

$$(x \leq -x_p)$$

- Majority carriers are injected across the junction and become minority carriers
- Minority carrier concentrations decay exponentially with distance from the junction edges back to their thermal equilibrium values
- Majority carrier concentrations are assumed to not deviate significantly from their thermal equilibrium values

Quasi Fermi Levels

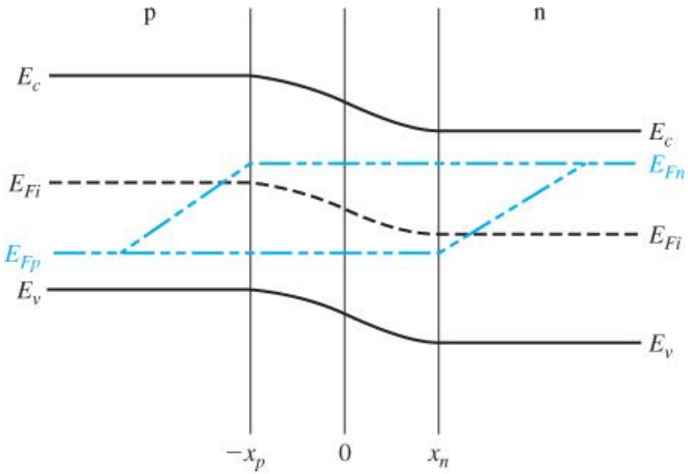


Figure 8.6 | Quasi-Fermi levels through a forward-biased pn junction.

$$\boxed{p = p_0 + \delta p = n_i exp\left(\frac{E_{Fi} - E_{Fp}}{kT}\right)}$$

$$\boxed{n = n_0 + \delta n = n_i exp\left(\frac{E_{Fn} - E_{Fi}}{kT}\right)}$$

- Quasi Fermi levels are applied to non-equilibrium conditions
- E_{Fn} and E_{Fp} are assumed to be constant within the depletion region and are linear with distance in the quasi-neutral regions on the opposite side
- Quasi-Fermi-level separation is related to the applied bias
- $E_{Fn} - E_{Fi} > 0$ means $n > n_i$ and $E_{Fi} - E_{Fp} > 0$ means $p > n_i$

Minority Carrier Current Densities

- The total current is the sum of the individual electron and hole currents, which are both constant in the depletion region
- We assume the electric field is zero at the depletion region edges, so all current at the edges is diffusion current
- The total current is the sum of the minority carrier electron current at x = $-x_p$ and the minority carrier hole current at x = x_n

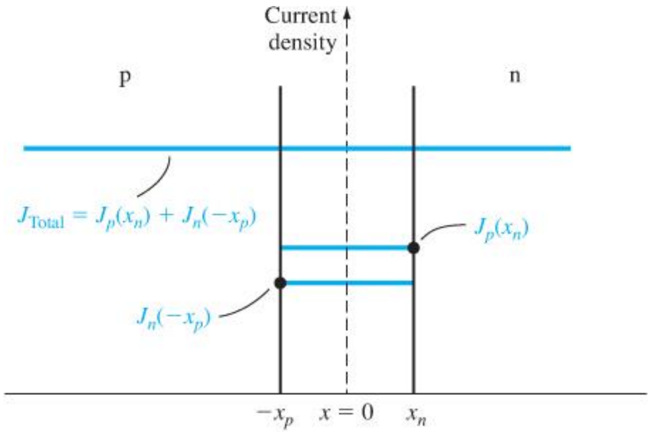


Figure 8.7 | Electron and hole current densities through the space charge region of a pn junction.

$$J_p(x_n) = \frac{eD_p p_{n0}}{L_p}\left[exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

$$J_n(-x_p) = \frac{eD_n n_{p0}}{L_n}\left[exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

*Both hole and electron currents are in the +x direction (from the p-side to the n-side)

Ideal Diode Equation

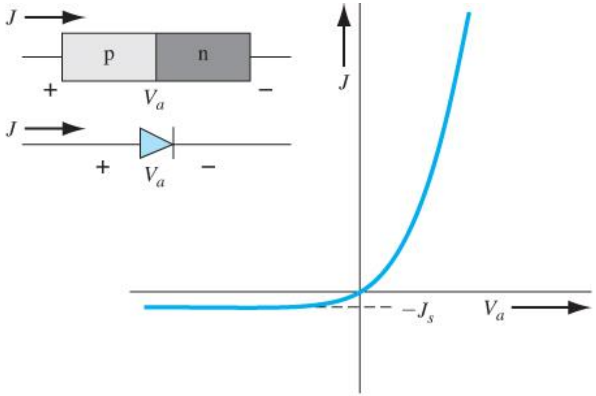


Figure 8.8 | Ideal *I–V* characteristic of a pn junction diode.

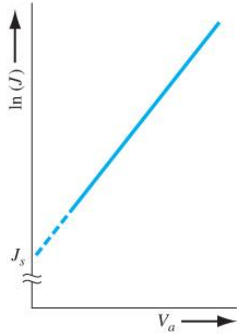


Figure 8.9 | Ideal *I–V* characteristic of a pn junction diode with the current plotted on a log scale.

- The total pn junction current is the sum of the minority carrier current densities at the depletion region edges

Ideal Diode Equation:

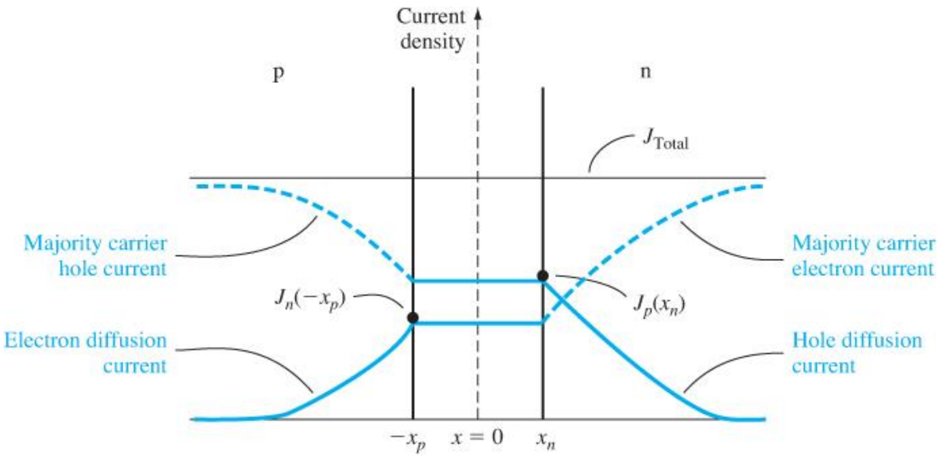
$$\boxed{J = J_p(x_n) + J_n(-x_p) = J_s\left[exp\left(\frac{eV_a}{kT}\right) - 1\right]}$$

Reverse saturation current density:

$$\boxed{J_s = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]}$$

- The forward bias current is an exponential function of applied bias
- The reverse bias current is nearly independent of bias (V_a can be negative)

Summary of pn Junction Currents



$$\boxed{J_p(x) = \frac{eD_p p_{n0}}{L_p}\left[exp\left(\frac{eV_a}{kT}\right) - 1\right] exp\left[\frac{x_n - x}{L_p}\right]}$$

$$(x \geq x_n)$$

$$\boxed{J_n(x) = \frac{eD_n n_{p0}}{L_n}\left[exp\left(\frac{eV_a}{kT}\right) - 1\right] exp\left[\frac{x_p + x}{L_p}\right]}$$

$$(x \leq -x_p)$$

- The total current at any point in the junction is the sum of the majority and minority carrier currents
- Hole current dominates on the p-side. Electron current dominates on the n-side. Both currents contribute in the depletion region.
- Away from the junction, current is dominated by drift
- Near and within the junction, current is dominated by diffusion